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THE PRE- AND POST-ACCRETION IRRADIATION HISTORY OF COMETARY ICES

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Comets Halley and Wilson exhibited similar 3.4μm emission features at ~1 AU from the Sun. A simple model of thermal emission from organic grains fits the feature, provides optical depths in good agreement with spacecraft measurements, and explains the absence of longer-wavelength organic features as due to spectral heliocentric evolution (Chyba and Sagan, 1987). The model utilizes transmission spectra of organics synthesized in the laboratory by irradiation of candidate cometary ices; we have long noted that related gas-phase syntheses yield polycyclic aromatic hydrocarbons, among other organic residues (Sagan *et al.*, 1967).

We have previously concluded (Chyba and Sagan, 1987) that Halley's loss of several meters' depth with each perihelion passage, combined with the good fit of the Halley 3.4μm feature to that of comet Wilson (Allen and Wickramasinghe, 1987), argues for the primordial—but not necessarily interstellar—origin of cometary organics. Here we examine the relative importance to the formation of organics of the variety of radiation environments experienced by comets. We conclude that there is at present no compelling reason to choose any of three contributing mechanisms (pre-accretion uv, pre-accretion cosmic ray, and post-accretion radionuclide processing) as the most important.

The irradiation environments experienced by cometary ices (summarized in the accompanying table) may be divided into four categories: (1) Pre-accretion irradiation of interstellar dust by uv and low-energy cosmic rays, (2) Post-accretion irradiation of cometary interiors by incorporated radionuclides, (3) Cosmic ray irradiation over 4.6 Gyr of a comet's outer ~ 10–100 m, and (4) Solar wind and ultraviolet irradiation to a depth $\lesssim$ 0.1μm during a comet's typically ~1 Gyr residence in the inner Oort cloud, ~3.5 Gyr residence in the outer Oort cloud, and eventual passage(s) through the inner solar system.

Even for a dynamically new comet such as Wilson, environment (4) will be unimportant for the formation of observable organics, as the outer 0.1μm of surface will be quickly shed during a comet's first passage through the inner solar system.

Ryan and Draganić (1986) have calculated the irradiation of a comet's outer layers by cosmic ray protons with energies >1 MeV. Cometary ice at a depth of 1 m experiences a dose ~10^4–10^5 Mrad; at 10 m, a dose ~10^3 Mrad; and negligible dose at much greater depths. Environment (3) may thus be contributing organics to the spectrum of the dynamically new comet Wilson, but not to that of Halley.

Below a depth ~10 m, radionuclides incorporated into the comet at the time of its accretion [environment (2)] provide a dose ~10^3 Mrad throughout the entire cometary interior (Draganić *et al.*, 1984). About 80% of this dose would have been due to the extinct radionuclide ^{26}Al, thus dating from the first ~10^6 yr of a comet's lifetime. Such a calculation takes $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$, as implied by isotopic analysis of meteorites, and assumes essentially cosmic abundances for most other elements. There is reason to believe this ^{26}Al abundance to be typical of

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bulk interstellar dust composition, as three independent γ-ray measurements (by HEAO 3, the SMM satellite, and a balloon flight) find $^{26}Al/^{27}Al \sim 1 \times 10^{-5}$ in the ISM (Wasserburg, 1987). A ratio $^{26}Al/^{27}Al \sim 10^{-5}$ would melt no more than the innermost core of a comet $\sim$5 km in radius (Wallis, 1980).

Both uv and and low–energy cosmic ray irradiation should significantly process volatile ices on grains in the ISM [environment (1)]. Over a $\sim 10^8$ yr molecular cloud residence, interstellar grains experience $\sim 10^7$ Mrad due to uv photons (Greenberg and Grim, 1986), and 5×10^4 Mrad due to low–energy cosmic rays (Strazzulla *et al.*, 1983). Both doses may increase substantially for those grains cycled between diffuse and dense clouds, although optically–thick clouds will shield dust from uv.

Strazzulla *et al.* (1983) have experimentally measured polymerization cross–sections for 0.1–2 MeV protons on C–rich ices; they conclude that, at the cosmic ray doses cited above, C–containing molecules in interstellar grains will be totally polymerized in times less than typical cloud lifetimes. Thus the fact that a grain's uv dose may be $\sim 10^2$–10^3 times that due to low–energy cosmic rays is not decisive for the two mechanisms' importance to the formation of interstellar organics. Even in the total absence of uv processing (as in an optically thick cloud), complete polymerization of C–containing ices would occur.

Comets must contain both solar nebula and interstellar condensates; the former may well be non–negligible (Geiss, 1987). C–containing solar nebula condensates will be irradiated by incorporated cometary radionuclides; the resulting dose $\sim 10^3$ Mrad should polymerize more than half of the C atoms present (Strazzulla *et al.*, 1983). Thus it appears that both pre– and post–accretion environments may be of importance for the formation of cometary organics. We are undertaking a well–characterized study of the infrared spectral evolution of candidate ice residues, with irradiation extending from radionuclide to interstellar doses. These experiments may exclude one or more irradiation environments: Only certain doses may yield spectra providing good fits to the 3.4μm feature in comets Halley and Wilson.

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COMET HALLEY IRRADIATION HISTORY

ENVIRONMENT	DOSE (Mrad)	PROCESSING DEPTH	REMARKS
Inner Solar System			
Solar Wind, 1 Orbit	10^3	$\sim 0.1\ \mu m$	Comet Shielded Within ~ 5 AU
Solar Wind, $10^2 - 10^3$ Orbits	$10^5 - 10^6$	$\sim 0.1\ \mu m$	
Residence in Oort Cloud			
Solar Wind, 4.6 Gyr	10^4	$\sim 0.1\ \mu m$	
Cosmic Rays, 4.6 Gyr[a]	$10^4 - 10^5$ 10^3	~ 1 m ~ 10 m	Flux May Increase Beyond Heliosphere
Radionuclides, 4.6 Gyr[a]	10^3	Entire Nucleus	Assumes no Differentiation ^{26}Al $\sim 80\%$
Inner Oort Cloud			
Solar Wind, $\sim$ Gyr	10^9	$\sim 0.1\ \mu m$	
Pre-Accretion			
Low Energy Cosmic Rays[b] $10^7 - 10^8$ yr	$10^4 - 10^5$	$\sim 100\ \mu m$	All C-containing Ices Polymerized
Interstellar UV, 10^8 yr[c]	$10^7 - 10^8$	$\sim 0.1\ \mu m$	

[a] Draganić et al., 1984.

[b] Strazzulla et al., 1983.

[c] Greenberg & Grim, 1986.